

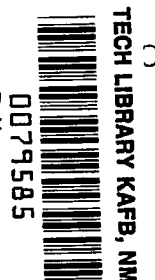
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by Arthur J. Glassman

Lewis Research Center

Cleveland, Ohio



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SUMMARY

This report summarizes the Brayton cycle space-power system analytical studies conducted at the Lewis Research Center. Presented herein are a description of the Brayton cycle, its thermodynamic behavior characteristics, component features and requirements, and weight and reliability considerations.

The Brayton cycle is considered suitable for low- and intermediate-power applications where low specific weight is not a prime requirement. In order to be suitable for high-power-level electric propulsion applications, turbine-inlet temperatures in the 3000° R range appear necessary. The Brayton cycle has a relatively good potential for being developed to a state of high reliability.

Good system performance depends on the proper selection of the system temperature ratios and the achievement of high component performance. The choice of both fluid molecular weight and system pressure level must result from compromising opposing effects on heat-transfer component and turbomachinery performance. High-temperature levels are desired to reduce radiator size, but materials limitations in the heat source and turbine must be respected.

INTRODUCTION

For a variety of space missions, both manned and unmanned, there exists a need for systems capable of generating power for many thousands of hours of continuous operation. Power levels range from a few kilowatts for auxiliary (nonpropulsive) use to many megawatts for manned missions utilizing electric propulsion to reach the other planets of our solar system. Powerplant specific weight (powerplant weight per kilowatt power output) for the high-power-level systems must be kept low because of the large inherent size of these systems and/or the strong dependency of electric rocket performance on the powerplant weight (ref. 1). Low specific weight, however, is not so critical a requirement for the low- and intermediate-power-level auxiliary powerplants.

The most promising power generation system for near future application to missions requiring power levels of several kilowatts or more is the indirect

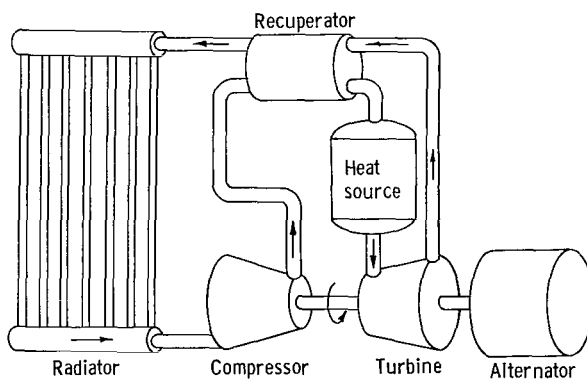
closed-loop conversion system, in which heat is generated by a nuclear or solar source and rejected by a radiator, with power being obtained from a turbine located in the working-fluid loop. The radiator has been shown to be the largest component and a major weight contributor to the powerplant. For high-power-level systems it may constitute half or more of the total weight. Much attention has been given to a vapor-liquid (Rankine) system using a metal working fluid, since this system has a much better thermodynamic potential than a gas (Brayton) system for obtaining the low radiator specific areas and weights required for large power-output applications. For power systems of several hundred kilowatts or less, however, where low specific weight is not so critical a requirement, the Brayton cycle merits strong consideration because it has many features that give it the potential of being a more reliable system. In addition, much of the basic technology for the Brayton cycle is presently available, especially at turbine-inlet temperatures of about 2000°R and below, through the jet-engine and gas-turbine power production fields.

In view of the interest in the Brayton cycle for space-power systems, a panel of Lewis staff members undertook an exploratory study of such systems and their components for both nuclear and solar heat-source applications. The thermodynamic, heat-transfer component, turbomachinery, weight, and reliability characteristics of Brayton cycle space-power systems were investigated and reported in detail in references 2 to 5. The pertinent results of these studies are summarized herein.

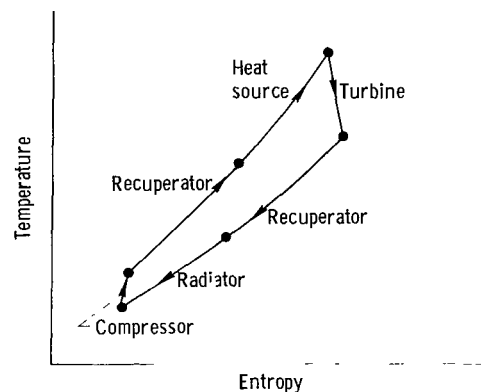
CYCLE CHARACTERISTICS

Description

Several configurations have been considered for Brayton cycle space-power systems. The simplest of these, the one-loop system, is shown schematically in figure 1(a) and thermodynamically in figure 1(b). The gaseous working fluid is heated to its maximum temperature in the heat source (nuclear reactor or solar heat absorber) and then expanded through the turbine, where the mechanical power required to drive the compressor and alternator is produced. In the



(a) Schematic diagram.



(b) Temperature - entropy diagram.

Figure 1. - Brayton power cycle.

recuperator, the turbine exit gas is cooled as it transfers heat to the compressor exit gas. Final cooling of the gas to the minimum cycle temperature takes place in the radiator, where the excess heat is rejected to space. The gas is then compressed, heated in the recuperator, and returned to the heat source.

If a liquid-metal-cooled reactor is used as the cycle heat source, a heating loop with a liquid-to-gas heat exchanger must be added to the system. The liquid-metal heat-transfer fluid circulates continuously between the reactor and the heat exchanger, which now serves as the heat source for the gas loop. This two-loop system has the advantages of better isolation of fission products and separation of reactor and power-system development problems; however, system complexity has increased. Reactor availability would probably influence the choice between a one- or two-loop scheme.

If a liquid radiator is used instead of a gas radiator, a cooling loop with a gas-to-liquid heat exchanger must be added to the system. The liquid coolant, which can be metallic, organic, or aqueous depending on the temperature level, circulates continuously between the heat exchanger, which now serves as a heat sink for the gas, and the radiator. A liquid cooling loop offers the possible advantages of lower weight and/or added mission reliability due to ease of segmentation (i.e., use of several loops in parallel to supply the required cooling); however, any advantages are offset to some extent by an increase in system complexity and a probable increase in radiator area.

Thermodynamics

The thermodynamic characteristics of Brayton cycle space-power systems were presented in detail in reference 2. Cycle performance characteristics were determined as a function of the cycle temperature variables (ratio of compressor-inlet to turbine-inlet temperature and ratio of turbine-exit to -inlet temperature) and the component performance parameters (pressure loss, turbomachinery efficiency, and recuperator effectiveness). The cycle temperature variables were then optimized and cycle performance was related to component performance. The choice of optimum values for the cycle temperature variables, as will be subsequently explained, depends on the relative importance of cycle efficiency as opposed to radiator area for any given system.

The manner in which the cycle temperature variables affect cycle performance is shown in figure 2, where relative cycle efficiency and radiator area are plotted against the ratio of compressor-inlet to turbine-inlet temperature (cycle temperature ratio) for several values of the ratio of turbine-exit to -inlet temperature (turbine temperature ratio). Relative cycle efficiency and relative radiator area are merely cycle efficiencies and radiator areas computed by the methods of reference 2 and then normalized so as to emphasize variable effects rather than performance levels. At each cycle temperature ratio there is a particular value of turbine temperature ratio that maximizes cycle efficiency and another value that minimizes radiator area. An increase in cycle temperature ratio results in a decrease in maximum achievable cycle efficiency. There is an optimum cycle temperature ratio that minimizes radiator area. This radiator area minimization is due to the trade-off between decreas-

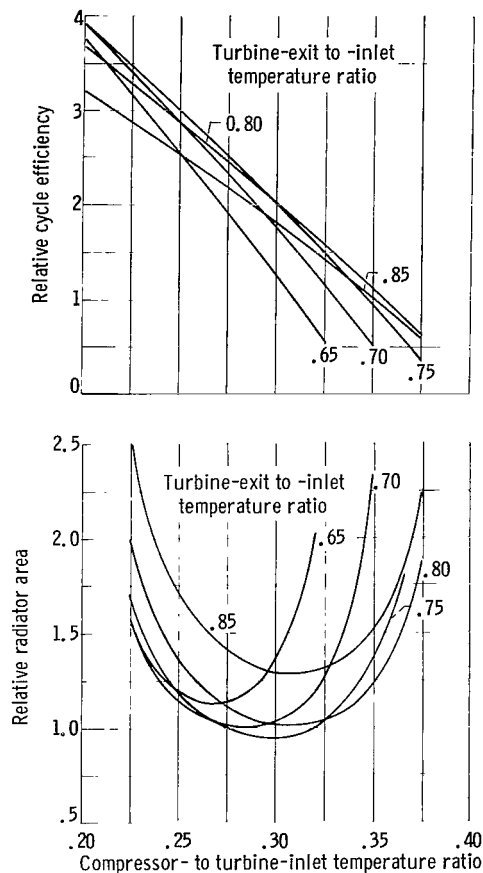


Figure 2. - Effect of cycle temperature variables on cycle efficiency and radiator area.

ing cycle efficiency and increasing radiator temperature with increasing cycle temperature ratio. The optimum values for the cycle temperature variables depend on the particular values of the component performance parameters. For performance parameters in the range of those usually encountered in a system, the minimum-area values for turbine temperature ratio and cycle temperature ratio are generally in the ranges 0.70 to 0.80 and 0.25 to 0.35, respectively.

For an intermediate- or a high-power reactor system, the predominant size and weight of the radiator result in the cycle temperature variables being selected primarily on the basis of radiator size minimization. For low-power radioisotope and solar applications, heat-source limitations (availability for radio-isotope systems and collector size for solar systems) result in a strong desire for high cycle efficiency in order to obtain maximum power from the given heat-source component. The cycle temperature variables for these low-power systems, therefore, are selected on the basis of obtaining higher cycle efficiencies at the expense of larger specific weights and areas for the radiator.

For a Brayton cycle system, cycle performance is a very strong function of component performance. Three important component performance parameters are pressure loss, turbomachinery efficiency, and recuperator effectiveness. Figure 3(a) illustrates how relative radiator area and cycle efficiency vary with system pressure loss. System pressure loss is equal to one minus the ratio of turbine pressure ratio to compressor pressure ratio, and this is approximately equal to the sum of the fractional pressure drops across the individual heat-transfer components. Inspection of figure 3(a) shows that both cycle efficiency and radiator area are very sensitive to pressure loss. For example, increasing the pressure loss from 0 to 20 percent approximately doubles the radiator area and reduces the cycle efficiency by about 30 percent. Thus, it is evident that one of the requirements for the heat-transfer components is that they be designed for low pressure loss.

The effect of the turbine and compressor efficiencies on relative radiator area and cycle efficiency is shown in figure 3(b). Turbomachinery component efficiency is here defined as the condition of equal turbine and compressor efficiency at the specified value. An 80-percent turbomachinery component efficiency, therefore, means an 80-percent turbine and an 80-percent compressor efficiency. This figure shows that both radiator area and cycle efficiency are very sensitive to turbomachinery component efficiency. For example, reducing the efficiency from 90 to 80 percent approximately doubles the radiator area

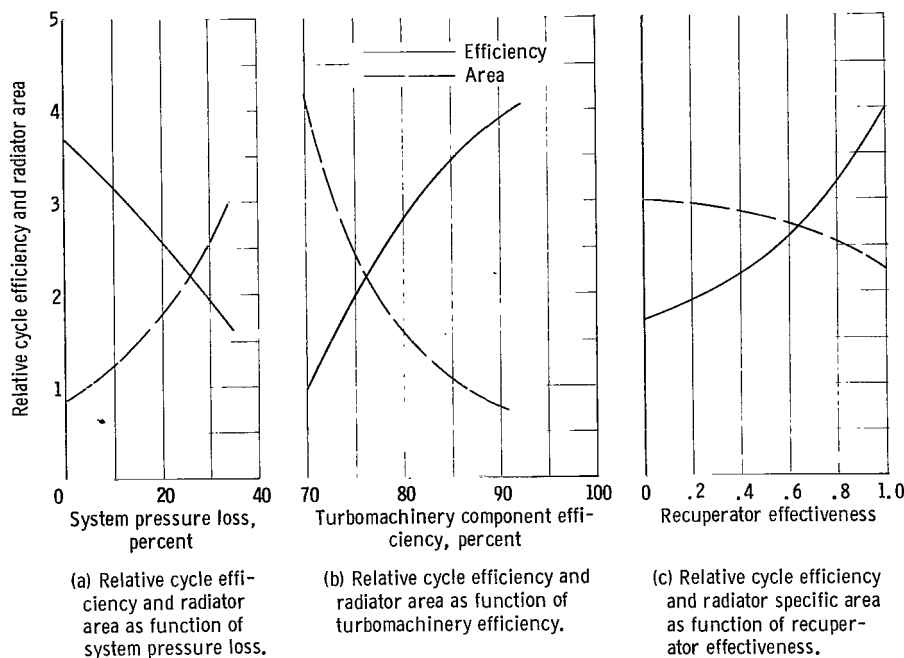


Figure 3. - Effect of component performance parameters on cycle efficiency and radiator area.

and reduces the cycle efficiency by about 28 percent. Thus, it is evident that good turbomachinery component efficiency is a prime requirement.

Figure 3(c) shows the effect of recuperator effectiveness on relative radiator area and cycle efficiency. Recuperator effectiveness is here defined as the actual temperature drop for the fluid in the recuperator as a fraction of the maximum temperature drop available (turbine exhaust temperature minus compressor exhaust temperature). A value of zero represents the case where a recuperator is not used; a value of 0.85 is considered a reasonable design value that can be used without encountering excessive recuperator weight. By considering these two values, it can be seen that the use of a high-effectiveness recuperator in the system approximately doubles the cycle efficiency. The effect on the radiator area, however, is not nearly so pronounced; the area reduction is only about 18 percent. Although the heat to be rejected is reduced by a factor of more than 2, the most efficient part of the radiator, the hot part, is eliminated; therefore, the effect on area, although significant, is considerably less than on the heat rejected. An additional advantage of a recuperator is that it helps the radiator from a structural standpoint by decreasing the radiator peak temperature by several hundred degrees. From these considerations, a high-effectiveness recuperator is desired, particularly when a high cycle efficiency is important.

COMPONENT CHARACTERISTICS

The heat-transfer component characteristics were discussed in detail in references 3 and 4, while the turbomachinery component characteristics were discussed in detail in references 4 and 5. These characteristics depend to a great extent on system working fluid, pressure level, and temperature level.

This section discusses the general effects of the previously mentioned system parameters on the components.

Working Fluid

The inert gases were of principal interest for this study. Selection of the inert gases results in an absence of chemical interaction of the working fluid with structural and containment materials and, therefore, in greater flexibility of material selection. The inert gases considered include helium, neon, argon, krypton, and xenon, which vary greatly in molecular weight (from 4 to 131).

Heat-transfer components. - The effect of fluid choice on heat-transfer component performance is presented in figure 4, where the relative ratio of heat-transfer coefficient to pressure drop for a fixed heat-exchanger geometry

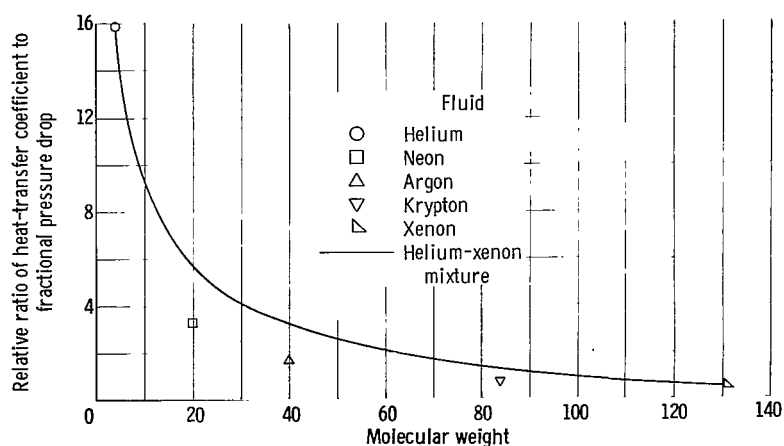


Figure 4. - Effect of molecular weight on heat-transfer component performance.

is plotted against working-fluid molecular weight for the pure inert gases as well as for helium-xenon mixtures. Such a relation is obtained by means of the Reynolds or Colburn analogy between heat transfer and flow friction by assuming a constant molal flow rate, as would be the case for a Brayton cycle of a given power output. This ratio, whose value should be high for favorable heat-exchanger performance, is inversely proportional to molecular weight for the

pure gases. For inert-gas mixtures, such as those for helium and xenon shown in figure 4, the ratio of heat-transfer coefficient to pressure drop is greater than that for a pure gas at the same molecular weight. On the basis of these heat-transfer - pressure-drop characteristics, the heat exchangers are seen to operate most efficiently with a low-molecular-weight fluid, such as helium. An example of this effect will be presented during the subsequent pressure-level discussion.

The desirability of low-molecular-weight fluids is also evident when consideration is given to two potential nuclear problems that appear when a gas reactor is used as the heat source. The first problem deals with the effect, if any, of the coolant on the reactivity of the reactor. In the temperature and pressure ranges being considered for this cycle, the atomic densities of the gases are 3 to 4 orders of magnitude less than the densities of liquid-metal coolants. None of the gases, with the possible exception of xenon, has an unusually large probability of absorbing or scattering neutrons, so the volume occupied by the gas is treated as a void in the reactor. A gaseous coolant, therefore, does not compete for the neutrons required to produce fis-

sion in the fuel and in this respect has no effect on reactivity.

The second potential problem is activation of gases passing through the reactor. In this case, the only source of radiation that has been considered as coming from the activated gas is the gamma radiation. Neutrons, alphas, and betas should not be a problem. To calculate the absolute dose to the payload is extremely difficult; however, an estimation of the relative dose or dose rate indicates small values for helium and neon and considerably larger values for argon, krypton, and xenon. Dose as used here is simply a measure of the energy absorbed in a material. In general, gamma radiation does comparatively little damage to the materials but can be quite harmful to human tissue. On the basis of extremely pessimistic assumptions, the dose to the payload is negligible when any of these gases is used; consequently, no radiation problem exists in the unmanned application. In regard to manned application, helium and neon will be acceptable, while the higher molecular weight gases may or may not be acceptable, depending on the type of reactor selected. Compared with radiation coming directly from the reactor, the gas represents a very small source; however, the reactor is compact and somewhat approaches a point source compared, for example, to the coolant source from the larger radiator. This is important for shielding considerations, which may or may not be a problem, depending on the application involved.

Turbomachinery. - The choice of working fluid affects the turbomachinery primarily in two ways: (1) the number of stages required for the attainment of the required pressure ratio at high efficiency and (2) the Reynolds number and size. The effect of molecular weight on number of stages for a constant turbine-inlet temperature is presented in figure 5 for both radial and axial turbomachinery. Figure 5 shows that the required number of stages is large for

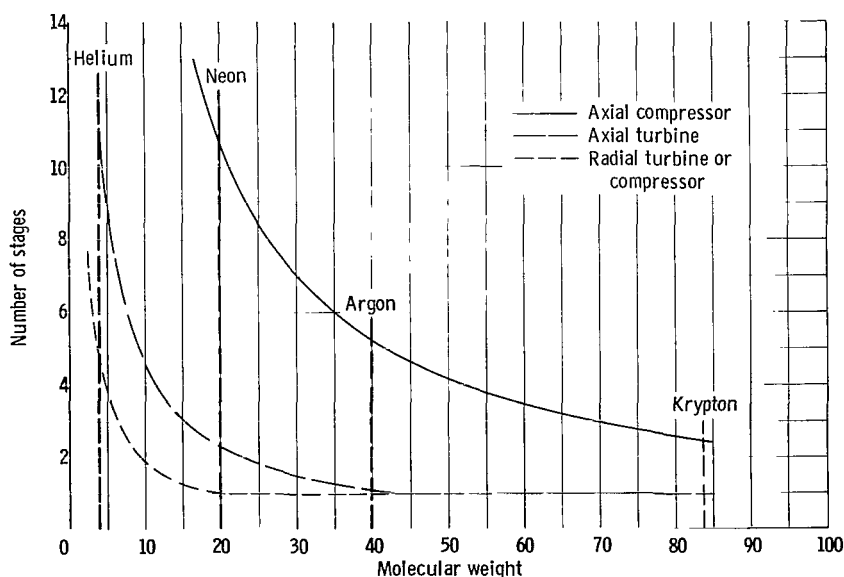


Figure 5. - Effect of molecular weight on number of turbomachinery stages; constant turbine-inlet temperature.

is about three to five times the number of axial turbine stages.

Reynolds number is directly proportional to weight flow and inversely proportional to viscosity for a given machine size. The relative Reynolds numbers for the fluids of interest (assuming helium as unity) are 1 for helium, 3.3 for neon, 8.4 for argon, and 15.1 for krypton. A general trend of Reynolds-number effects on axial-flow-compressor efficiency is presented in figure 6 (based on the compilation of data presented in ref. 6). This figure indicates that there is a reduction in achievable efficiency as Reynolds number

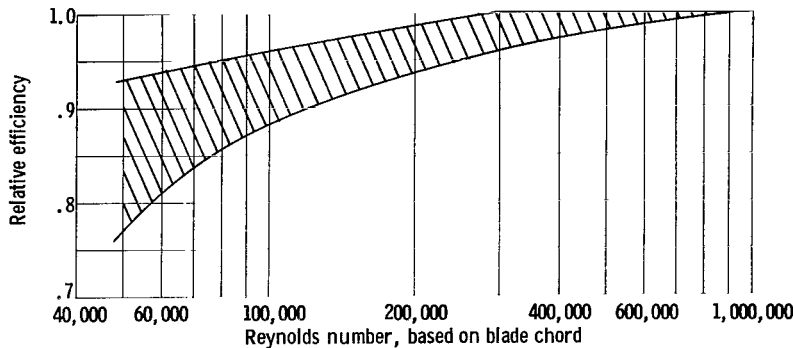


Figure 6. - Effect of Reynolds number on axial-flow compressor efficiency.

decreases below 10^6 , and this reduction becomes more pronounced with further decreases in Reynolds number. With argon as the working fluid, typical Reynolds numbers range from about 10^6 at the 1000-kilowatt power level to less than 10^5 at the 10-kilowatt power level. For neon, the corresponding Reynolds numbers are reduced by a factor of about 2.5. At the

low power levels, consequently, compressor performance may very well be affected by Reynolds number considerations. If operation should occur at a point where the effect of Reynolds number on performance is significant, the use of a low-molecular-weight gas could result in a significant deterioration in performance. Similar considerations affect turbine performance but not to the same extent as compressor performance.

Pressure Level

Heat-transfer components. - As noted previously, high heat-transfer coefficients and low pressure drops are desired for the heat-transfer components.

The effect of pressure on heat-exchanger performance is shown in figure 7, where the relative ratio of heat-transfer coefficient to pressure drop is plotted as a function of pressure for a fixed heat-exchanger geometry. This ratio, aside from being inversely proportional to molecular weight as shown previously, is also directly proportional to pressure squared. Consequently, at 100 pounds per square inch this ratio is 25 times its value at 20 pounds per square inch. Because of this heat-transfer - pressure-drop characteristic, high pressures are desired for the heat-transfer components. An example of the effects of pressure and molecular weight on one of the heat-transfer components is presented in figure 8, where radiator relative area and weight are plotted against pressure level for example cases with helium, neon, and argon as the working fluids (unpublished NASA data). Both pressure and fluid effects can be quite significant. For example, at a pressure level of 75 pounds per square inch absolute the use of argon rather than neon results in about a 10-percent increase in area and a

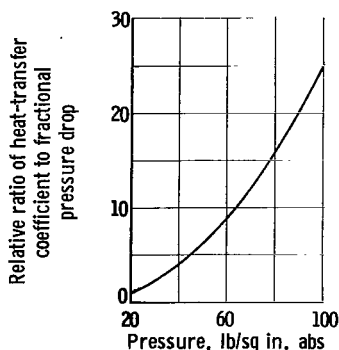


Figure 7. - Effect of pressure level on heat-transfer component performance.

15-percent increase in weight; for neon, a reduction in pressure from 100 to 50 pounds per square inch absolute results in about a 10-percent increase in area and a 30-percent increase in weight.

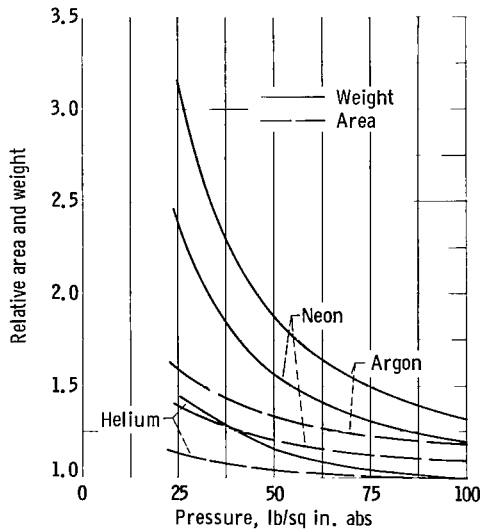


Figure 8. - Effects of pressure level and fluid type on radiator area and weight.

Turbomachinery. - The effect of pressure level on the turbomachinery is primarily in the area of machine size (diameter). Typical curves for the diameter of an axial-flow turbine as a function of pressure are presented in figure 9 for system power levels of 10, 100, and 1000 kilowatts. For any given power level, diameter is inversely proportional to the square root of pressure. For a 10-kilowatt system, an increase in turbine-inlet pressure from 5 to 30 pounds per square inch absolute results in a decrease in diameter from 10 to 4 inches. For other power levels the pressures corresponding to similar diameters are in direct proportion to the power.

The size of a turbine or compressor appears to affect the achievable efficiency level. With decreasing diameter, factors

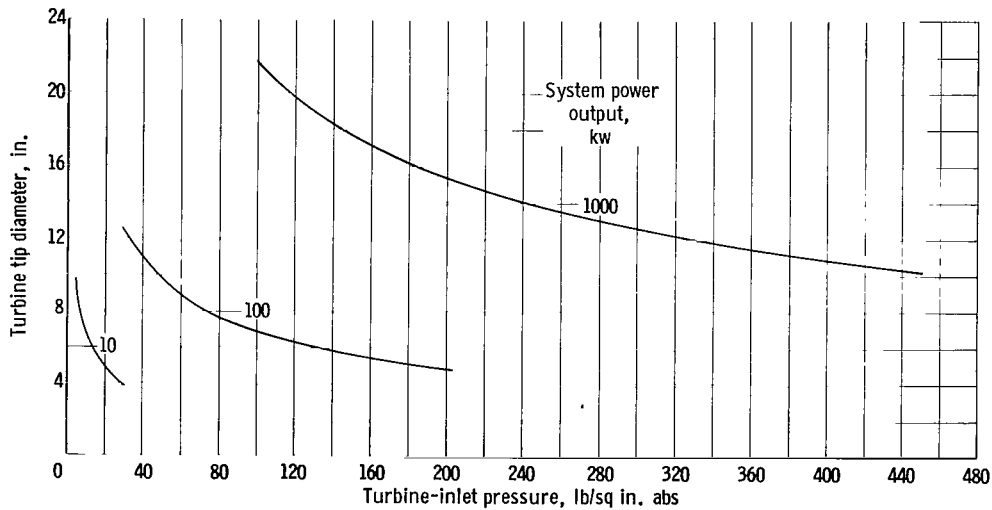


Figure 9. - Effect of inlet pressure on axial-flow turbine diameter.

such as tip clearance losses and decreasing Reynolds number have a pronounced effect on overall efficiency. The exact magnitude and extent of this size effect is not well defined. For the achievement of high efficiency, however, relatively large size turbomachinery appears to be desirable. Pressure level, consequently, must be chosen so that the turbomachinery does not become too small to achieve high efficiency. Since the heat-transfer components benefit from relatively high pressures, the selection of a system pressure level must be made on the basis of a compromise.

As power level increases, the pressure level corresponding to a given turbomachinery diameter increases in direct proportion. Consequently, turbomachinery with a given geometry can be used in systems of different power outputs by appropriately adjusting the pressure level. As power output increases, the allowable system pressure can increase and, as pointed out previously, this benefits the heat-transfer components. For a given set of turbomachinery, the amount of pressure increase, of course, is governed by the maximum allowable design stress of the component casing and by the bearing load capability due to the higher axial-thrust loads on the rotors. Even with a redesign of the casing and running gear, pressure level cannot be increased indefinitely with power level because a limiting pressure level, as dictated by system structural considerations, is eventually reached. Studies have indicated that the limiting pressure level is reached at approximately the 200- to 400-kilowatt power level. At power levels above this, pressure can be maintained constant and turbomachinery diameter will increase as the square root of power.

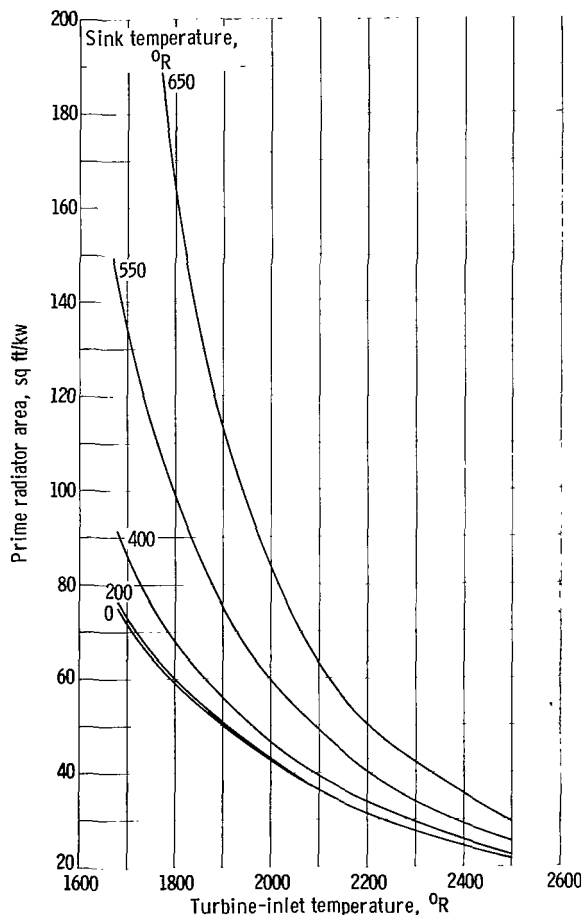


Figure 10. - Effect of turbine-inlet and sink temperatures on prime radiator area.

Temperature Level

The components that are affected to a great extent by temperature level are the radiator, whose size is extremely temperature dependent, and the heat source (nuclear reactor or solar heat absorber) and turbine, since the latter two components operate in the area of peak temperature.

Radiator. - The effect of turbine-inlet temperature on prime radiator area for several sink temperatures is shown in figure 10. Prime radiator area can be defined as the radiating surface required with a radiator having a fin effectiveness of 100 percent. Comparison of prime radiator area with the actual area of a flat-plate finned-tube radiator (unpublished NASA data) showed that the ratio of actual area to prime area is about 1.6. At a turbine-inlet temperature of 1700° R and a sink temperature of 400° R the required prime radiator area is greater than 80 square feet per kilowatt of output power. Brayton cycles operating at this temperature would require hundreds or thousands of square feet of radiator area depending on the power level.

For the 400° R sink temperature, an increase in turbine-inlet temperature from 1700° to 2500° R results in a four-fold decrease in radiator area. This temperature effect is primarily due to the proportionality of radiation heat flux to the fourth power of temperature. Considering the large radiator size re-

quired for a turbine-inlet temperature of 1700°R , an increase in turbine-inlet temperature above this level is extremely advantageous to the system.

If the turbine-inlet temperature is high, the sink temperature has a relatively small effect on radiator area. As the turbine-inlet temperature is reduced below approximately 2000°R , however, the sink temperature becomes an important factor because the radiator-exit temperature begins to approach the sink temperature and the net radiation heat flux from the exit end of the radiator becomes quite low. While a value of 400°R may be an average value for sink temperature, a satellite could possibly encounter sink temperatures as high as 600°R depending on its orientation or the condition of its emitting surface. If rated power is required of the system regardless of its orientation, the radiator must be sized appropriately for the high sink temperatures. For a turbine-inlet temperature below 2000°R , the required radiator area for a sink temperature of 650°R is more than double that for 400°R . Thus, it is clear that, from a radiator standpoint, the highest turbine-inlet temperature feasible should be utilized.

Heat source. - Temperature limitations, however, occur in the heat source and the turbine. These are material limitations associated with the structural materials as well as the reactor moderator and solar-heat absorbent materials. The heat source limitations depend on the particular type of heat source used and will be discussed later in association with the component descriptions. In regard to the turbine, even if one of the best high-temperature alloys is used, the reduction in strength of the material results in a required decrease in rotor blade speed.

Turbine. - The required number of turbine stages as a function of inlet temperature, with argon as the fluid, is presented in figure 11 for both axial-

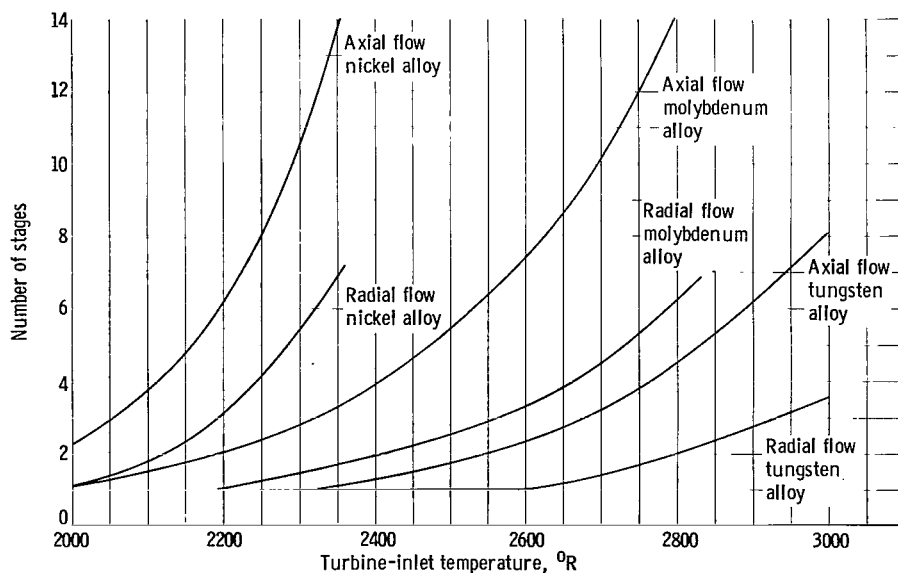


Figure 11. - Effect of turbine-inlet temperature on number of turbine stages. Working fluid, argon.

and radial-flow turbines, each with typical high-strength rotors of nickel, molybdenum, and tungsten alloy. As turbine-inlet temperature increases, the

number of stages increases rapidly. For the case of a molybdenum-alloy rotor the number of stages for an axial-flow turbine increases from 1 to 14 as turbine-inlet temperature increases from 2000° to 2800° R, while for a radial-flow turbine the required number of stages increases from 1 to 6 as turbine-inlet temperature increases from 2200° to 2800° R. For a tungsten-alloy rotor the number of stages is about one-third that required with a molybdenum alloy, while for a nickel-alloy rotor the number of stages is two to four times that with a molybdenum alloy. This variation in number of stages reflects the stress-to-density ratios of these materials.

Although the compressor is not directly affected by a temperature limitation, it is indirectly affected through the required reduction in turbine rotational speed with increasing turbine-inlet temperature. This results in the number of compressor stages increasing with an increase in turbine-inlet temperature. As was mentioned previously, the number of radial-flow-compressor stages is equal to the number of radial-flow-turbine stages, while the number of axial-flow-compressor stages is about three to five times the number of axial-flow-turbine stages.

COMPONENT DESCRIPTIONS

The previously discussed thermodynamic considerations and system parameter effects result in a set of desirable requirements for the components. A general description of the components needed to satisfy these requirements is presented in this section.

Heat Source

A major consideration in the selection of a cycle heat source is the maximum fluid temperature that can be obtained from that source. For the case of a gas-cooled heat source, this temperature will be the turbine-inlet temperature; for a liquid-metal-cooled heat source, the turbine-inlet temperature must be somewhat less than the heat-source exit temperature because of the intermediate liquid-to-gas heat-transfer step. The potential heat sources for Brayton cycle systems are radioisotope (about 1 to 5 kw of output power), solar (about 5 to 40 kw), and nuclear reactor (about 30 kw and greater). Detailed investigations of radioisotope and solar heat sources were not conducted. The radioisotope systems were assumed to have peak temperatures of about 2000° R. Solar heat absorption fluids of interest were sodium fluoride (2280° R melting point) and lithium fluoride (2020° R melting point).

Several types of reactor systems have been developed, but not all are applicable to space-power systems. The reactor property known as criticality results in some reactor configurations that are extremely large and, therefore, not usable. Other reactors are of the desired small size, but cannot produce the required temperature. Because it is desirable to operate the gas system at turbine-inlet temperatures above 2000° R, as was previously shown, and the fuel elements must operate 400° to 500° R hotter than the exhaust gas, the reactor will probably have to use refractory metals to maintain the necessary strength. Two types of reactors can be considered, the heterogeneous thermal and the

fast reactors.

In the heterogeneous thermal reactor, the neutron moderator and fuel elements are in separate regions; it is possible, therefore, to have the fuel elements at a higher temperature than the moderator and, thereby, be able to obtain the desired high temperature while using some of the better moderator materials. An example of a Brayton cycle power system using a heterogeneous thermal reactor is the ML-1 powerplant. This is a land-based Brayton system designed to produce 300 to 500 kilowatts of electricity and to attain a turbine-inlet temperature of 1660°R , a value that is considered too low for space application.

The best high-temperature gas-cooled reactor operating experience has been obtained with this type of reactor as part of the Heat-Transfer Reactor Experiment (HTRE) of the now cancelled Aircraft Nuclear Propulsion (ANP) program. Considerable success was achieved in operating a reactor with a gas-outlet temperature approaching 2000°R . The HTRE reactor is unsatisfactory for space-power systems because of its large size and high power level (30 mw). The development of a smaller reactor producing the same gas-outlet temperature and having a weight usable for space-auxiliary-power applications is a design problem requiring, at most, a modest extension of existing technology. Such a size reduction, however, has limitations unless the fuel-element temperature can be raised. The HTRE program stopped with the use of a high-nickel-alloy fuel element. A refractory-metal fuel element appears to be a reasonable next step.

The reactor concept that appears most desirable is the fast spectrum reactor. This reactor is of minimum size, although possibly not of minimum weight. It is called fast because the fission process is caused by neutrons of fast velocity or high energy. As a result, it does not need a neutron moderator and can operate at temperatures limited only by the fuel-element structural material. Considering its present state of development, the successful design, construction, and operation of a high-temperature fast reactor is probably 5 years or more in the future, and there are probably many problem areas that have not yet been discovered. One example of a fast reactor under development for space-power systems is the liquid-metal-cooled Snap-50 reactor.

Heat Exchangers

The heat exchangers include the recuperator and, if a multiloop system is used, the gas heater and/or cooler. Good system performance, as indicated previously, depends to a large extent on the obtainment of low-weight heat exchangers that operate with high effectiveness and low pressure drop. The choice of configuration for the Brayton cycle heat exchangers appears to be the compact extended surface units such as the finned-tube and plate-fin types. Rotating matrix configurations have the potential for reducing recuperator weight; however, the problem of leakage and carryover losses, which can be quite detrimental to system performance, must be studied before a rotating configuration can be considered. The inherent simplicity and reliability of the stationary surface configurations, as well as the availability of design data, resulted in the choice of these configurations for this study.

There are many compact heat-exchanger surfaces, as well as the heat-transfer and flow-friction data for these surfaces, presented in the published literature. In addition, there are also many proprietary designs for efficient and compact heat-exchanger surfaces. The most extensive study, known to the author, of compact heat-transfer surfaces was the work sponsored by the Office of Naval Research and performed at Stanford University during the past 15 years. Among the surfaces studied were finned-tube surfaces with both circular and flat tubes and plate-fin surfaces with a variety of fin types, such as plain, louvered, strip, wavy, pin, offset rectangular, and triangular.

Both the basic heat-transfer and flow-friction design data and the fabrication techniques are in existence for a large number of surface configurations. The extension of this technology for application to high-temperature heat exchangers, however, will require some development effort. In addition, the requirements of high effectiveness and low pressure drop yield configurations where the effects of axial heat conduction in the metal and manifold design are quite significant.

Radiator

The radiator for a Brayton cycle space-power system, as indicated previously, will require from hundreds to thousands of square feet of radiating area, depending on system power level and turbine-inlet temperature. Since the radiator must operate in outer space, where high-speed meteoroids are present, the fluid passages have to be protected against puncture by these meteoroids. Meteoroid protection is generally provided by a layer of armor around the fluid passages. The required armor thickness depends on such factors as meteoroid population density, meteoroid properties, radiator material properties, radiator size, mission time, and desired protection probability. Unfortunately, there is still much uncertainty concerning the values of some of these factors and the exact manner in which they influence required armor thickness. The requirement for meteoroid protection armor can result in the radiator being extremely heavy and possibly accounting for more than half of the total system weight. Before the design and fabrication of a large space radiator is attempted, consideration must be given to methods for reducing its size and/or weight. Such factors as external fin and tube configurations, tube size, armor material, internal fins, and a liquid cooling loop can significantly affect radiator size and/or weight.

Radiator geometry has an important effect on radiator size and weight. Finned-tube radiators, although requiring larger areas than unfinned radiators, offer a considerable weight saving over the unfinned radiators. This weight saving results primarily from the fact that only the tubes have to be armor protected against meteoroid puncture; the fins, consequently, can be reasonably thin. A minimum weight finned-tube configuration can be obtained for any application by an optimization procedure utilizing a trade-off between decreasing tube area, which must be armored, and increasing radiator size with decreasing fin effectiveness.

An example of the effect of radiator geometry on radiator weight is shown in figure 12 for a system power output of 100 kilowatts. An unfinned radiator

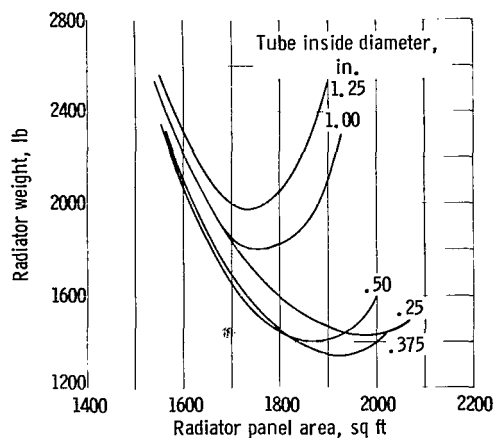


Figure 12. - Effect of radiator geometry on radiator weight. System electrical output, 100 kilowatts; turbine-inlet temperature, 2200° R; material, beryllium.

TABLE I. - ARMOR MATERIAL COMPARISON

Armor material	Relative thickness	Relative weight
Beryllium	1.00	1.00
Aluminum	1.53	2.30
Stainless steel	.86	3.93
Molybdenum	.80	4.07

for the example system shown would require a panel area of about 1230 square feet and would weigh about 6000 pounds. As seen from figure 12, an optimum finned-tube configuration requires about 1930 square feet of panel area but weighs only 1350 pounds.

The choice of armor material also has a significant effect on radiator weight. Armor thickness and weight depend on both the density and the modulus of elasticity of the armor material (ref. 7). For several armor materials of interest, the relative thicknesses and weights for equivalent protection are tabulated in table I. The tabulated values refer to flat plates; for tubes, these ratios will vary somewhat. Beryllium appears to have a considerable weight advantage as a meteoroid armor material.

Another important consideration as far as radiator area is concerned is the heat-transfer coefficient of the fluid in the radiator. If the heat-transfer coefficient is low, a considerable temperature drop, possibly in excess of 100° R, occurs between the fluid and the tube wall. This can occur primarily in low-power-output systems where, as indicated previously, the gas pressure must be fairly low in order to achieve reasonable turbomachinery geometries. Such a temperature drop is detrimental to the radiator and can result in a large increase in required area. For such cases, there are several things that can be done. Internal fins can be placed in the radiator in order to increase greatly the ratio of internal to radiating area and, thereby, increase the heat-transfer rate between the gas and the wall. Another alternative is the use of a liquid cooling loop, since the heat-transfer coefficients associated with liquids are usually much higher than those associated with gases.

A liquid radiator, as indicated previously, offers a potential weight saving over a gas radiator. Panel area, however, will be larger for the liquid radiator because of the lower temperature and larger tube-to-tube distance for a minimum weight configuration. The weight saving potential of the liquid radiator can be attributed to the following factors: (1) smaller tube and header sizes due to the much greater density of the liquid, (2) larger allowable pressure drops because of the very small amount of power required to pump liquids, (3) larger heat-transfer coefficients of liquids, and (4) less armor thickness due to the smaller vulnerable area. An additional potential advantage is that of increased mission reliability achieved through the use of several cooling

loops in parallel. The disadvantages associated with a liquid radiator are the added complexity of a cooling loop, the additional weight of a gas cooler and a pump, and the larger radiator area. The choice of gas cooler effectiveness and liquid flow rate can be based on a minimization of the total weight of gas cooler and radiator.

Many areas must be explored and problems solved before large efficient space radiators become a reality. Prominent among these areas that need clarification and/or development are (1) meteoroid population density, (2) meteoroid penetration mechanism, (3) fabrication of beryllium into radiators, (4) surface coatings with favorable absorptivity-emissivity properties, (5) techniques for the analysis of complex internal and external finned-tube geometries, and (6) segmentation techniques.

Turbomachinery

The selection of turbomachinery for any system design involves choices between axial-flow and radial-flow machines and between a single turbine or separate turbines for driving the compressor and the alternator. The decision whether to use radial-flow or axial-flow turbomachinery is usually based on achievable performance level, which can be related to the required number of stages and the rotor-tip diameter. Where multistaging is required, a purely radial-flow configuration appears to be less attractive than other possible configurations. The required ducting and associated duct losses for multistage radial-flow configurations reduce their potential for achieving maximum efficiencies. For situations requiring multistaging, therefore, the best choice appears to be a purely axial-flow machine or, in cases requiring a large number of stages, possibly a hybrid configuration (one radial stage plus axial stages).

As far as single-stage machines are concerned, a radial-flow configuration appears to be of the most advantage where small sizes are required. In the region of small tip diameters, about 5 inches and less, the performance of radial-flow machines is less sensitive to flow surface imperfections than is the performance of axial-flow machines. The amount of tip clearance must be held as small as possible since this clearance has a significant effect on the performance of axial-flow machines, especially those with small blade heights. For small size radial-flow machines, clearances are not as critical. In addition, the small throat areas required for small diameter axial-flow turbines present problems in fabrication because of the required close tolerances.

The single-stage radial-flow machine, therefore, appears most suitable for use in the small-size region since performance is less sensitive to size effects. For larger machines these small-size effects become less pronounced, and the axial-flow machine may very well outperform the radial-flow machine.

There are two possible arrangements for the turbomachinery components. These are a single turbine that is directly coupled to the compressor and alternator and a dual (split) turbine arrangement whereby one turbine drives the compressor and the second turbine drives the alternator. The dual turbine arrangement appears to be attractive for situations where alternator require-

ments dictate comparatively low rotative speeds while compressor requirements dictate high rotative speeds. If frequency requirements are 400 cycles per second, for example, the required speed for the alternator would be 24,000 revolutions per minute at maximum and very possibly just 12,000 revolutions per minute. Such a rotative speed in conjunction with the small diameters often encountered could result in an excessive number of stages for the compressor. A dual turbine system would allow both the alternator and the compressor to operate at optimum speeds without the need for a speed reduction gearbox.

Another feature of the dual turbine arrangement is that it results in lower turbine-exit kinetic-energy losses when compared to the single turbine arrangement. Typical exit losses for the single turbine arrangement (without a diffuser) are approximately 6 to 10 percent of turbine work, while exit losses for the dual turbine arrangement are about 2 to 3 percent of the total turbine work. The low-speed alternator turbine, therefore, serves as an efficient diffuser.

The previous pressure-level discussion indicated that, for power levels up to several hundred kilowatts, turbomachinery diameter should be maintained approximately constant at as small a size as is consistent with good performance. At present, this minimum tip diameter is believed to lie in the range of about 4 to 6 inches. Turbomachinery features typical of an 8-kilowatt Brayton power system are presented in table II.

TABLE II. - TURBOMACHINERY FEATURES FOR 8-KILOWATT BRAYTON POWER SYSTEM

	Compressor		Compressor turbine		Alternator turbine	
	Radial	Axial	Radial	Axial	Radial	Axial
Inlet temperature, °R	536	536	1950	1950	1685	1685
Inlet pressure, lb/sq in. abs	6.0	6.0	13.2	13.2	8.45	8.45
Pressure ratio	2.30	2.30	1.56	1.56	1.26	1.26
Stages	1	6	1	1	1	2
Tip diameter, in.	5.38	4.25	5.51	5.50	12.90	9.34
Rotational speed, rpm	42,000	44,700	42,000	44,700	12,000	12,000

WEIGHT AND RELIABILITY CONSIDERATIONS

In all of the areas of application being considered, reliable operation over extended periods of time (years) is a prime requirement. The severity of need for low system weight, however, depends on the intended use of the system.

Weight

The discussion of weight will be made in terms of two systems of interest;

namely, the solar and nuclear-reactor systems.

Solar system. - The solar systems being considered are for output power levels up to about 40 kilowatts. Limitations in the power level are dictated by the size limitations of the solar collector, which becomes quite large at powers above this level. The intended use of the solar system is auxiliary in nature; therefore, low specific weight is not a prime requirement. For these systems, the radiator weight shares importance with the weights of the solar collector and heat storage components. Minimizing the size of the collector and the total weight of the components is achieved through high cycle efficiencies, which can be obtained through the use of the recuperated gas system. Representative weights evolved for these systems are in the 200- to 300-pound-per-kilowatt range, which, as noted previously, does not represent a restriction on the suitability of the solar system for its intended use. These weights, of course, depend to a large extent on the type of solar collector used and the assumed meteoroid protection criteria. A solar Brayton cycle system designed for an electrical output of about 8 kilowatts is described in reference 8.

Nuclear-reactor system. - The discussion of the weight characteristics of the nuclear system will indicate some of the major factors affecting the weight of the system and show the general level of total specific weight of the major components (hereinafter termed system ideal specific weight) as a function of output power level and turbine-inlet temperature. In this way, an appraisal can be made of the suitability of this system for such an application as power generation for propulsion, where specific weight is important.

The major components included in the computation of total weight were reactor, reactor shield (1000 lb assumed), recuperator, radiator, turbine, compressor, and alternator. It is important to note that the computed weights

(1) are for an unmanned application where the shielding requirements are relatively low, (2) do not include any allowance for support structure, and (3) do not include power-conditioning equipment. In addition, the gas radiator was assumed to be constructed of beryllium. The use of other radiator materials would have a severe effect on the specific weights shown.

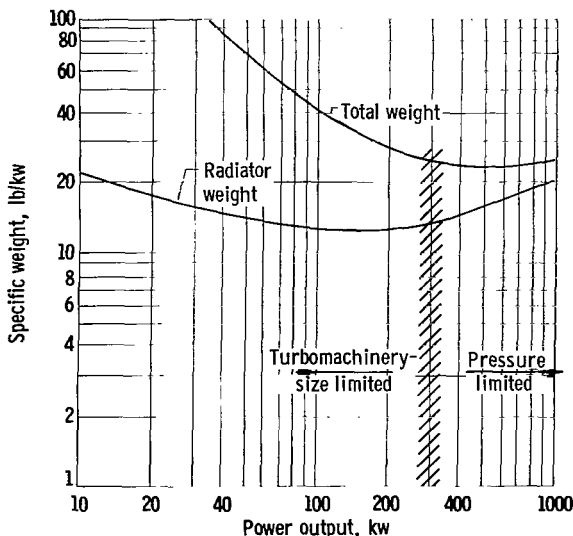


Figure 13. - Example effect of power level on nuclear Brayton system ideal specific weight. Turbine-inlet temperature, 2500° R.

Figure 13 presents both radiator and system ideal specific weight as a function of power level for a turbine-inlet temperature of 2500° R. A power level of 300 kilowatts, for which the compressor exit pressure would be about 500 pounds per square inch absolute, was chosen as the power level corresponding to the previously mentioned pressure limit. Pressure was assumed to vary linearly with power up to 300 kilowatts

and remain constant at values beyond this.

As power level increases above the pressure limit value, the radiator specific weight increases as the 0.3 power of power level. This reflects the additional meteoroid protection required for the larger radiator area. As power level decreases below the pressure limit value, radiator specific weight decreases to a minimum value and then increases at the lower power levels as a result of the decreasing pressure level. At low powers (50 kw or less), the total specific weight is high, exceeding 50 pounds per kilowatt. A minimum specific weight occurs in the 500-kilowatt area at about 25 pounds per kilowatt, with the radiator representing about two-thirds of this weight. At power levels above this value, the specific weight increases principally because of the radiator weight, which now becomes very dominant.

System ideal specific weight as a function of power level is presented in figure 14 for turbine-inlet temperatures of 2000°, 2500°, and 3000° R. The

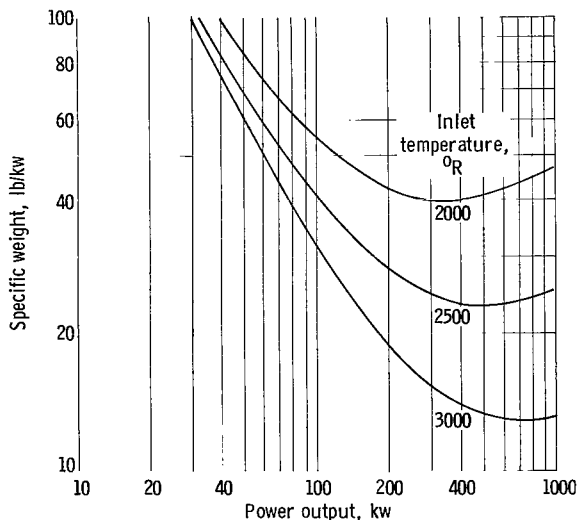


Figure 14. - Effect of power and temperature levels on nuclear Brayton system ideal specific weight.

effect of temperature level on total weight depends on the power level because of the large effect of temperature on radiator weight. At low power levels, where the radiator weight is a relatively small contributor to total weight, very little effect is seen. At high power levels, where the radiator weight is predominant, the effect of temperature on total weight is quite large. There is considerable incentive, therefore, to increase the turbine-inlet temperature to as high a value as possible for the high-power-level systems. From the standpoint of minimum specific weight, the nuclear Brayton system is most attractive in the submegawatt range (200 kw to 1 mw). Turbine-inlet temperatures in the 3000° R range are required to reduce the specific weight

of the major components to a level of interest (about 10 to 20 lb/kw) for electric propulsion. Shielding, structure, and power-conditioning requirements can easily double the total weights presented herein.

The total weights presented in this report are for the major components only, are very preliminary, and are intended to indicate principally levels and trends. The optimum powers and specific weights obtained are greatly dependent on the amount of shielding, the additional weight required for support structure and power-conditioning equipment, and the selected radiator material. Large increases in weight due to any of these factors would greatly increase the level of specific weight and shift the optimum to lower power levels. At the higher power levels where the radiator specific weight becomes very predominant, the use of such weight-cutting techniques as segmenting becomes attractive. The manner of segmenting and such problems as sensing and valving

must still be evaluated, however, before the true potential of this approach can be determined.

Reliability

The previous discussion indicated that, because of the large radiator required, the specific weight of the gas system limits its use to applications where low specific weights are not required. For all the applications being considered, however, an extremely reliable system is required because space-power systems are expected to operate without maintenance for periods of 1 year or more.

From a fundamental reliability standpoint, both the Brayton and Rankine systems have a number of common areas of uncertainty. Among these are the reactor control and bearing development problems. A considerable number of problem areas, nevertheless, can be eliminated through utilization of a Brayton instead of a Rankine system. The pertinent difference that affects the relative reliabilities of the two systems is the use of a single-phase inert-gas working fluid in the Brayton system as opposed to a two-phase (liquid-vapor) metal working fluid in the Rankine system. This use results in either the elimination of or a great reduction in the severity of such problem areas from the Brayton system as corrosion, erosion, cavitation, material deposits, and zero-gravity flow stability. There are also fewer restrictions with respect to both containment material selection and fabrication techniques. The Brayton system, in addition, is very well suited for achieving multiple starts in space.

A second reliability area is that of developability. In order to bring any power system into a demonstrated high reliability of the level required for the intended missions, a very large number of component and system tests will be required. The gas system lends itself well to such a development program. Component performance tests are relatively simple to conduct and require little time. Few extended tests are required because the problems of extended operation are principally of a structural nature rather than due to corrosion and erosion. Facilities for developing the components of the gas system are comparatively simple and inexpensive because the components can be easily assembled and disassembled. Lastly, elaborate safety measures are not required for inert-gas systems at modest pressure levels.

CONCLUSIONS

This report summarized the Brayton cycle space-power system analytical studies conducted at the Lewis Research Center. The major points brought out by these studies were

1. The Brayton cycle is considered suitable for low-power radioisotope and solar systems and intermediate-power nuclear-reactor systems where low

specific weight is not a critical requirement. In order for Brayton systems to be suitable for electric propulsion applications, turbine-inlet temperatures in the 3000°R range at power levels in the 500 to 1000 kilowatt range appear necessary.

2. The Brayton cycle has a relatively good potential for being developed to the state of reliability necessary for the required long-time unattended operation. Areas requiring particular development emphasis include, but are not restricted to, gas-cooled reactors, large space radiators, gas-bearing technology, small-turbomachinery performance, and system control.

3. Minimization of radiator area can be achieved through optimization of appropriate system temperature ratios. The optimum values for cycle temperature ratio and turbine temperature ratio are generally in the ranges 0.25 to 0.35 and 0.70 to 0.80, respectively.

4. High component performance is necessary in order to make the Brayton cycle attractive as a space-power system. This includes low pressure losses and high turbomachinery efficiency. For systems where high cycle efficiency is essential, high recuperator effectiveness is also included.

5. The working-fluid molecular-weight range of 20 (neon) to 40 (argon) appears attractive for compromising the opposing effects of decreasing heat-transfer performance and increasing turbomachinery performance with increasing molecular weight. Binary mixtures of the inert gases offer improved heat-transfer characteristics when compared with pure gases of the same molecular weight. For nuclear systems, working-fluid activation also must be considered.

6. Optimum pressure level depends to a large extent on system power level. High pressure levels improve heat-transfer performance and decrease turbomachinery size. At low power levels, the minimum turbomachinery size consistent with good performance becomes the controlling factor that limits system pressure. As power level increases, associated increases in pressure level can be utilized.

7. High turbine-inlet temperatures, in excess of about 2000°R , are desired in order to maintain specific radiator area at reasonable levels. Materials considerations in the heat source and turbine, however, limit the peak temperature levels for any system.

Lewis Research Center

National Aeronautics and Space Administration

Cleveland, Ohio, July 1, 1964

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